A NUMERICAL INVESTIGATION OF TIDAL CURRENT CIRCULATION IN THE GULF OF MAINE

by

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THESIS

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ABSTRACT

The hydrodynamical-numerical model of Walter Hansen is used to compute tidal heights and tidal currents in the Gulf of Maine. The model uses two adjacent open boundaries at which the tides are prescribed at each time step, using four tidal constituents. The grid size is six nautical miles and the time step is thirty-one seconds. Seven data runs are reported; one uses the tides and no wind and the remaining six use uniform wind fields in consort with the tides. A modified method of handling the topographic data is used. The pertinent results of the study are: (1) the use of Hansen's Model with adjacent open boundaries produces broad subjective agreement with observed data, (2) the modified method of handling topographic input data is workable, (3) wind direction and velocity produce slight variations in tidal height, (4) wind direction and velocity modify the direction of the tidal currents considerably and produce some significant increases in tidal current speed, and (5) the modifying influences of wind fields on tidal heights, tidal current velocities, and tidal current directions are more noticeable in shallow water areas than in regions of deep water.

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x,y	space co-ordinates
t	time
u,v	components of mean velocity
H	total depth
	water elevation in relation to the undisturbed sea surface
X,Y	external body forces
	wind stress components
g	acceleration of gravity
f	coriolis parameter
r	coefficient of friction
	Laplace operator
Ah	coefficient of horizontal eddy diffusivity
	density of water
N,M	horizontal and vertical grid co-ordinates (also n,m)
	average water elevation
u,v	average wind velocity components
2	half time step
	bottom friction
	hydrostatic pressure
	proportionality factor between the components of wind stress and the square of the wind velocity
a	numerical smoothing parameter
	grid size

H_{MAX}	maximum water depth
M2,K1,S2,N2	tidal constituents

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I. INTRODUCTION

The knowledge of the currents of the ocean, in adjacent and marginal seas, and in estuaries has long been of the utmost importance to navigators and inhabitants of coastal regions. Many attempts have been made to understand the currents produced by physical processes such as storm surges, tides, and ocean currents. Years of observations and measurements have resulted in a vastly increased knowledge of the physical processes of the sea. This knowledge has been applied in navigation, coastal engineering, commercial fishing, and in prediction of tides and tidal currents. There is a need for more thorough understanding of the physical processes of the ocean in order to cope with such modern problems as pollution, deep water salvage operations, mining the continental shelf, and farming the sea.

The need for this knowledge leads to questions concerning the possibilities of reproducing oceanic motions and how best to accomplish this goal. A successful model for reproducing oceanic motions leads to a capability to predict these motions and hence, hastens the possibility for various groups of people to benefit from the sea.

Oceanic motions produced in a numerical model must be compared with actual measurements. If the correlation is reasonably close, then some confidence may be placed in the model. After calibration, the model can be used to forecast with all the practical applications that this

implies. Electronic computers make the use of numerical models practical and reasonably economical. Numerical models are flexible in that the boundary conditions and variables involved are easily altered to meet changing needs. Hence, more extensive use is being made of numerical models in predicting physical motions of the sea.

The hydrodynamical-thermodynamical equations, in a general form, provide a background for understanding the problems of oceanic motions. These equations form the basis for the model developed by Dr. Walter Hansen at the Institut fur Meereskunde der Universitat Hamburg in 1935.

Hansen's model has been used to reproduce physical processes in a number of bays, tidal estuaries, and marginal seas. Examples include the North Sea, Baltic Sea, The English Channel, The Straits of Gibraltar, The Bosphorus, Persian Gulf, Chesapeake Bay, Long Island Sound, Danang Harbor, Tonkin Gulf, and the Gulf of St. Lawrence. Practically speaking, there are a large number of ocean areas where there is a need to determine oceanic physical processes which could be solved by numerical-hydrodynamic means.

The primary purpose of this study is to extend the coverage of the Hansen model to the region of the Gulf of Maine and to verify the model in this region. The determination of the general tidal circulation in this

region and the modifying effects of various wind fields on the tides and tidal currents is an objective of major importance. This is true for locations where data for comparison are available as well as for points such as those on the continental shelf and slope where no such data could be obtained.

The region of study includes the area between 40° and 45° North latitude and extends from 66°30' to 71°30' West longitude, a total area of 90,000 nautical miles. (Figure 1) This primarily oceanic area extends from the southern extremity of the Bay of Fundy near Grand Manan Island off the coast of Maine south to include Cape Cod, Nantucket Shoals, and nearby environs.

The bottom topography is irregular in the central Wilkinson Basin region. (100 fathom contours shown in Figure 1) It becomes more regular to the north approaching the Bay of Fundy, to the south in the Nantucket Shoals area, and as the coastline is approached. The underwater landscape is principally continental shelf, but in the lower southeast corner, the continental slope is crossed with an accompanying plunge in water depths from 100 fathoms or less to 1600 fathoms and deeper.

The land-sea border is rugged and frequently indented. This is particularly true along the coast of Maine. The various bays and inlets form an interesting and unusual coastline which includes several unique features. The most dominant feature is that of Cape Cod which extends

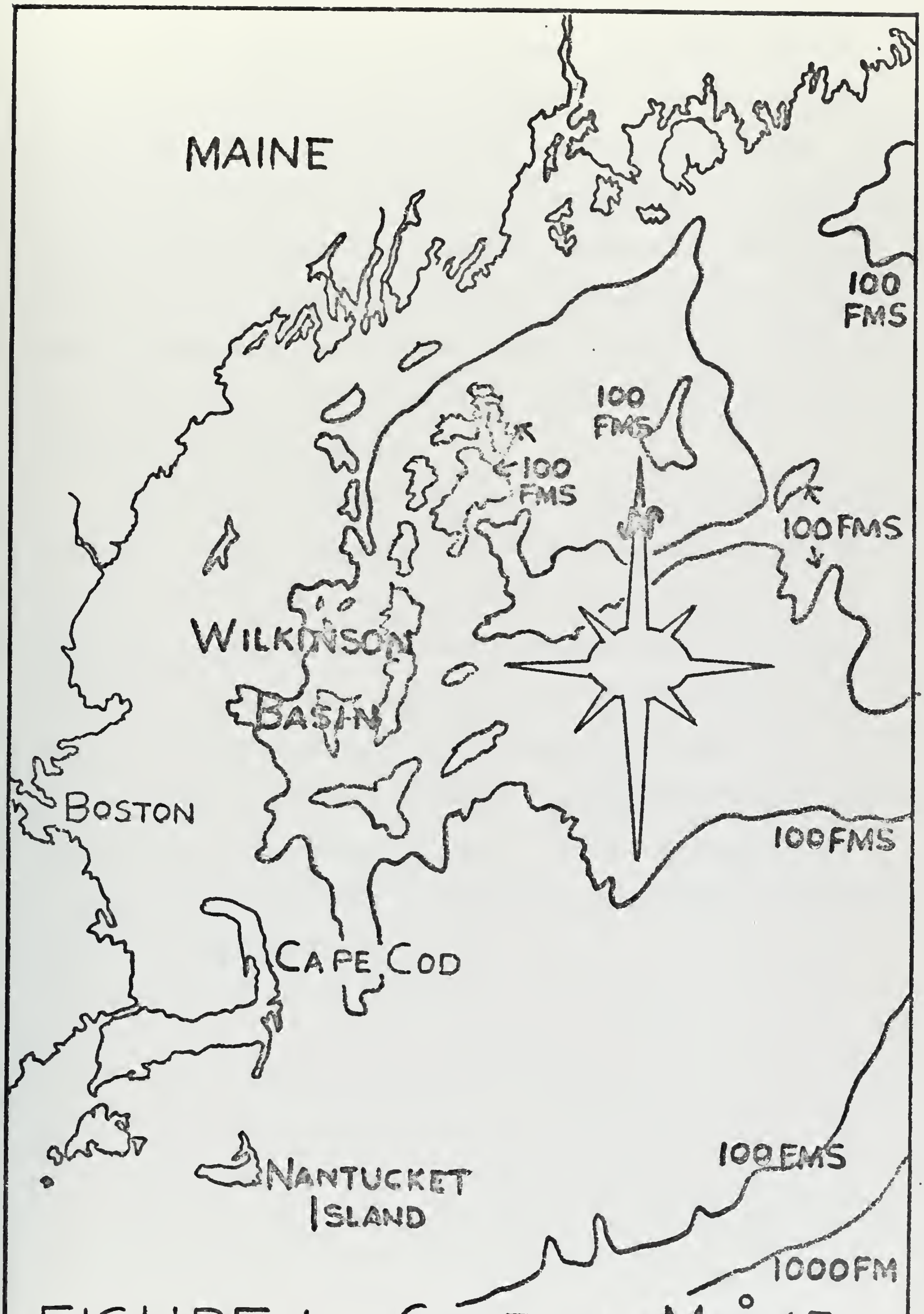

FIGURE 1 GULF OF MAINE

like a giant fishhook into the sea. The canal across Cape Cod is another unusual feature of the area as the tides and tidal currents at the eastern and western ends of that body make an interesting comparison. Several large islands such as Martha's Vinyard, Nantucket, and Grand Manan are all strategically placed to produce an influence upon oceanic motions that may be of interest. Finally, the large tidal constituents of the Bay of Fundy affect the Gulf of Maine region.

The Gulf of Maine is important for several reasons. There are large commercial fishing interests in the area. The port of Boston, Massachusetts, is an important maritime region as is the southern portion of the gulf where sea lanes carry trade between New York City and various world ports. Numerous hazards to maritime safety are attested to by the number of shipwrecks in the area, especially on Nantucket Shoals. There are many other reasons for the region's importance but these are perhaps the most important.

II. THE EQUATIONS

The classical problem of the tides in the world ocean can be stated: Determine the tides and tidal currents from hydrodynamical equations using the known tide generating forces and the geometry of the sea bottom and coastline. It is then possible to compute the tides and tidal currents quantitatively using the hydrodynamical differential equations without resorting to measurements of these quantities.

This problem has been studied since the time of Newton. Mathematicians and physicists such as Laplace, Bermoulli, Poincare, and others, have worked on the tidal problem. The common goal of their combined efforts was to solve the hydrodynamical equations analytically. Solutions were obtained only for geometrically simple oceans. Recently, Proudman and Doodson developed a method of computing ocean tides for regions bounded by meridians. In all these efforts, the essential influence of the depth distribution on the tides and tidal currents was considered in a geometrically simple manner. Considerable differences have been found to exist between tides and tidal currents in the actual ocean and those computed for geometrically simple oceans.

The equations used in Hansen's model are based on the hydrodynamical differential equations derived from the Navier-Stokes equation. They are the equations of motion:

$$\frac{\partial u}{\partial t} - fv - A_h \Delta u + \frac{r}{H} u(u^2+v^2)^{1/2} + g\frac{\partial \zeta}{\partial x} = X + \frac{\tau^{(x)}}{H} \quad (1)$$

$$\frac{\partial v}{\partial t} + fu - A_h \Delta v + \frac{r}{H} v(u^2+v^2)^{1/2} + g\frac{\partial \zeta}{\partial y} = Y + \frac{\tau^{(y)}}{H} \quad (2)$$

and the conservation of mass equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \quad (3)$$

where x and y are the space co-ordinates; t is the time; u and v are the components of the mean velocity; H is the total depth; ζ the water elevation in relation to the un-disturbed surface of the sea; X and Y are the external body forces; $\tau^{(x)}$ and $\tau^{(y)}$ are the wind stress components; g the acceleration of gravity; f the coriolis parameter; r the coefficient of friction between water and the sea floor; A_h the coefficient of horizontal eddy diffusivity; and Δ the Laplace operator.

The eddy diffusivity terms are interpreted as an averaging of the u and v components. Hansen states that the computations are always stable for A_h values greater than zero. He also uses an averaging coefficient, a, which is a function of A_h and of the local and temporal step length. (When A_h=0, a=1)

The tides, being long waves, extend their influence over the depth of the oceans. The equations, as stated,

are integrated from the sea floor to the sea surface. This reduces the number of variables and unknown functions by one. The two horizontal components of the averaged velocity over depth remain.

Another assumption involved in using these equations is that the pressure is hydrostatic and that the changes in pressure are due solely to changes in surface water elevation. Advection terms are considered to be small and are ignored when using these equations. This has been found to be a good assumption for long wave problems. These assumptions help bring equations (1),(2), and (3) into a more useable form. The problem of the geometry of distribution remains once these assumptions have been made.

The motions of the ocean are difficult to solve analytically, especially if the equations are used in their general, non-linear form. Analytical solutions require considerable simplification of the boundary conditions and the equations can only be solved for a basin of regular shape and simple wind distribution. The Gulf of Maine is irregular in shape, non-uniform in depth, and exhibits varied wind patterns. To deal with these problems an implicit method for achieving time dependent solutions to equations (1),(2), and (3) was developed using a finite difference approach. The resulting finite difference approximations are:

$$u^{t+2\tau}(n,m) = \Big\{1-\left[2\tau r/H_u^{t+2\tau}(n,m)\right]\left(\bar{u}^t(n,m)^2 + v^{*t}(n,m)^2\right)^{1/2}\Big\}\bar{u}^t(n,m) + 2\tau f v^{*t}(n,m) - \frac{\tau g}{\rho}\Big\{\zeta^{t+\tau}(n,m+1) - \zeta^{t+\tau}(n,m)\Big\} + 2\tau X^{t+2\tau}(n,m) \tag{4}$$

$$v^{t+2\tau}(n,m) = \Big\{1-\left[2\tau r/H_v^{t+2\tau}(n,m)\right]\left(\bar{v}^t(n,m)^2 + u^{*t}(n,m)^2\right)^{1/2}\Big\}\bar{v}^t(n,m) - 2\tau f u^{*t}(n,m) - \frac{\tau g}{\rho}\Big\{\zeta^{t+\tau}(n,m) - \zeta^{t+\tau}(n+1,m)\Big\} + 2\tau Y^{t+2\tau}(n,m) \tag{5}$$

$$\zeta^{t+\tau}(n,m) = \bar{\zeta}^{t+\tau}(n,m) - \frac{\tau}{\rho}\Big\{H_u^t(n,m)u^t(n,m) - H_u^t(n,m-1)u^t(n,m-1) + H_v^t(n-1,m)v^t(n-1,m) - H_v^t(n,m)v^t(n,m)\Big\} \tag{6}$$

The overbars indicate averaged terms where the averaged velocity and water elevation components are given by:

$$\bar{u}^t(n,m) = a\,u^t(n,m) + \frac{1-a}{4}\Big\{u^t(n-1,m) + u^t(n+1,m) + u^t(n,m+1) + u^t(n,m-1)\Big\} \tag{7}$$

$$\bar{v}^t(n,m) = a\,v^t(n,m) + \frac{1-a}{4}\Big\{v^t(n,m-1) + v^t(n+1,m-1) + v^t(n,m) + v^t(n+1,m)\Big\} \tag{8}$$

$$\bar{\zeta}^t(n,m) = a\,\zeta^t(n,m) + \frac{1-a}{4}\Big\{\zeta^t(n-1,m) + \zeta^t(n+1,m) + \zeta^t(n,m+1) + \zeta^t(n,m-1)\Big\} \tag{9}$$

The values of u^{*t}, v^{*t}, and ^{*t} in equations (4) - (6) are given by:

$$u^{*t}(n,m) = \frac{1}{4}\left\{u^{t}(n,m-1) + u^{t}(n+1,m-1) + u^{t}(n,m) + u^{t}(n+1,m)\right\} \tag{10}$$

$$v^{*t}(n,m) = \frac{1}{4}\left\{v^{t}(n,m-1) + v^{t}(n+1,m-1) + v^{t}(n,m) + v^{t}(n+1,m)\right\} \tag{11}$$

$$\zeta^{*t}(n,m) = \frac{1}{4}\left\{\zeta^{t}(n,m-1) + \zeta^{t}(n+1,m-1) + \zeta^{t}(n,m) + \zeta^{t}(n+1,m)\right\} \tag{12}$$

The half time step is given by 2τ. The depth in terms of H_u and H_v is approximated by:

$$H_u^{t+2\tau}(n,m) = hu(n,m) + \frac{1}{2}\left\{\zeta^{t+\tau}(n,m) + \zeta^{t+\tau}(n,m+1)\right\} \tag{13}$$

and

$$H_v^{t+2\tau}(n,m) = hv(n,m) + \frac{1}{2}\left\{\zeta^{t+\tau}(n,m) + \zeta^{t+\tau}(n,m+1)\right\} \tag{14}$$

The external body forces composed of the wind stress and barometric pressure anomoly are computed using the following formulas:

$$X^t = \frac{\tau^{(x)}}{H} - \frac{1}{\rho r}\frac{\partial P_0}{\partial x} \qquad (15)$$

and

$$Y^t = \frac{\tau^{(y)}}{H} - \frac{1}{\rho r}\frac{\partial P_0}{\partial y} \qquad (16)$$

The components of wind stress are expressed as:

$$\tau^{(x)} = \lambda W_x (W_x{}^2 + W_y{}^2)^{1/2} \qquad (17)$$

and

$$\tau^{(y)} = \lambda W_y (W_x{}^2 + W_y{}^2)^{1/2} \qquad (18)$$

The bottom friction is assumed a quadratic function of the velocity. The respective horizontal components are given by:

$$\tau^{(b)}_{(x,y)} = \frac{r}{H} u (u^2+v^2)^{1/2} \; ; \; \frac{r}{H} v (u^2+v^2)^{1/2} \qquad (19)$$

The partial derivatives in equations (1), (2), and (3) are replaced by finite difference approximations. The boundary values are then prescribed as known functions of time. The values of sea level and velocity are determined step by step by the difference equations starting from arbitrary initial values of the same quantities.

III. THE NUMERICAL MODEL

The model developed by Walter Hansen is based on four major conditions to obtain solutions: (1) that the equations of motion must be in a suitable form, (2) that the driving forces acting on the area of study are given, (3) that boundary and initial value conditions are specified, and (4) that the area of investigation is known in regard to coastal outline and depth distribution. These conditions are met in developing the Gulf of Maine model.

The equations used are in the form of the finite difference formulas given in the previous section. The driving forces acting in the area, including the tides at the open boundaries, the coriolis parameter, the direction and velocity of the wind field, the acceleration of gravity, and the coefficient of friction are specified to insure a uniquely determined solution. The open boundaries are specified and the tidal constituents along those boundaries are known. The depth distribution and coastal outline are obtained from U. S. Navy Chart BC 708.

The grid network used in the Hansen model is shown at the top of Figure 2. It consists of three separate sets of grid points: (1) the water elevation, or z points, at the grid intersections, (2) the u points located to the right of and midway between successive z points, and (3) the v grid points located vertically beneath and mid-way between successive z points. Each of these points is located by the same (N,M) co-ordinate

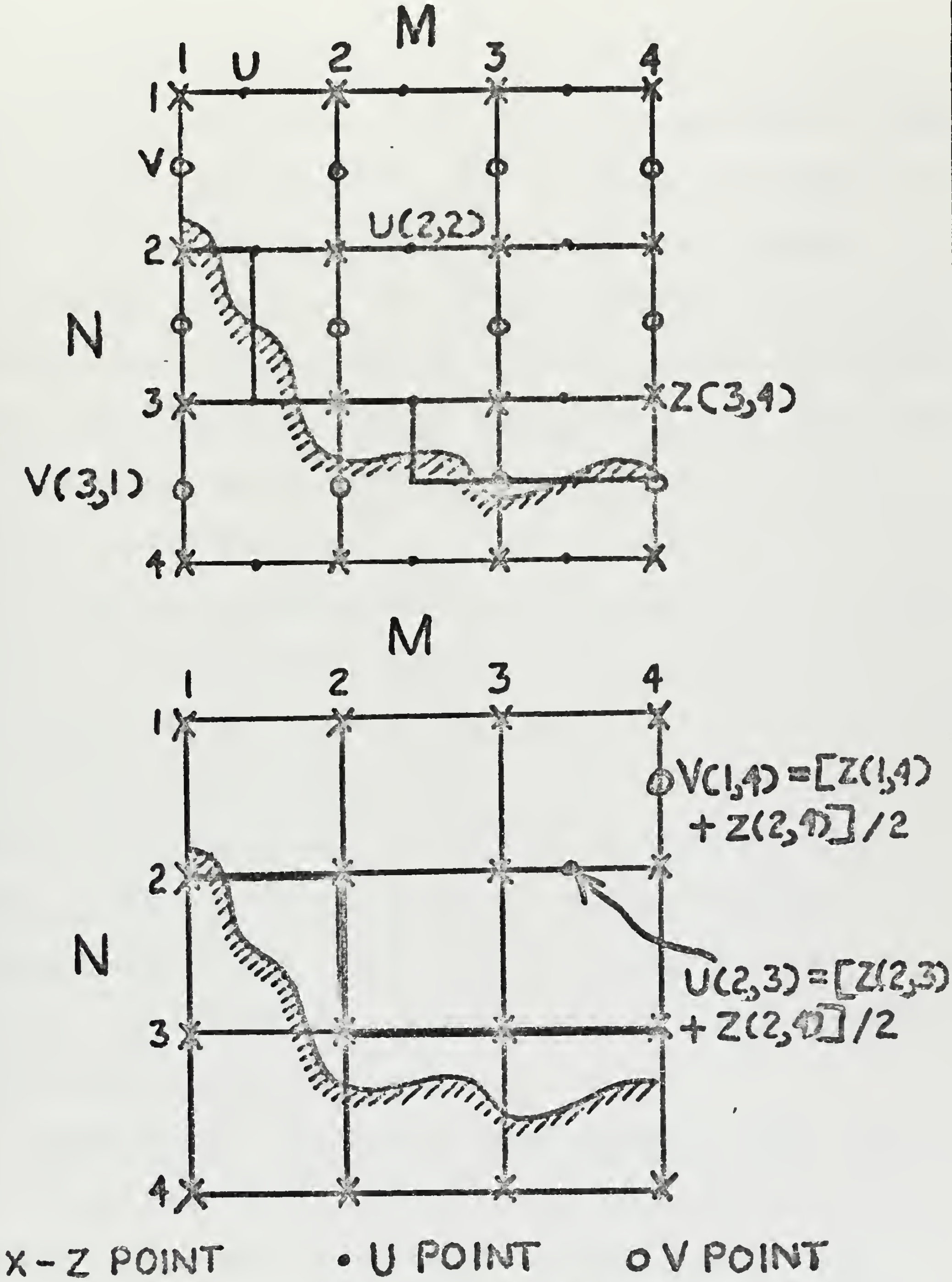

FIGURE 2 GRID NETWORKS.

designation. The N-axis is perpendicular to the first open boundary and the M-axis is parallel to that same input boundary.

This grid set-up requires the preparation of three separate sets of arrays. The first set consists of symbolic data for the z grid points. The z points are coded 0 for land, -1 for a land-sea boundary, and 1 for a point located over the water. The separate u and v data decks are also coded 0 for land and -1 for a land-sea boundary point. The oceanic points in the u and v data cards are coded with the charted depth, in centimeters, at the respective points.

The question arose early in this project as to the necessity of using three separate sets of data cards. The land and land-sea boundary areas are largely duplicated in the three data decks. Since both the u and v grid points are located half way between successive z grid points, another question arose as to the possibility of averaging successive z grid points horizontally and vertically and using those values at the u and v points without sacrificing accuracy.

Consequently, one set of data cards is used. The z grid points are used, coding 0 for land points, -1 for land-sea boundaries, and charted depth in centimeters for the oceanic points. This alternate grid network is shown at the bottom of Figure 2.

The use of only the z grid points for data make

several program changes necessary. The modifications consist of computing loops that average the values of successive z points horizontally and vertically to produce values of topography for the u and v points. These changes enter into the program in the initial data handling subroutine.

Problems arose using the averaging process in this study to obtain data for the u and v grid points. The effect of averaging a boundary point, coded -1; with either a land point, coded 0; or an oceanic point, coded with charted depth in centimeters; is to produce a boundary point. This creates boundaries that are too wide. The result is that islands become larger than they really are and that narrow, restricted channels are closed. The latter effect is apparent in the Grand Manan Channel at the northeast corner of the area.

The first few runs of the program ended with errors as the values for the tidal height in the Grand Manan Channel rose as high as one thousand centimeters. This is above built in program limits and is an unreasonable height for the tide in this area.

The process of correcting the boundary points involves additional arithmetic function statements to spot correct the points found to be in error. It is not useful to do any revamping of the z grid points. The u and v points are corrected with direct statements changing those points that require alteration in value.

This program requires the changing of one hundred three values at u points and sixty-four of the values at v grid points. These changes enable the program to run to completion.

Figure 2 also shows typical boundaries using Hansen's procedure and the revised method. In Hansen's method, at the top of the figure, a step type boundary is shown. This boundary is drawn to the u and v points as it blocks off the coastline. In contrast, the revised method shows a step type boundary that is drawn to the z points to accomplish the same objective. The revised method offers less flexability in adjusting the boundary to the coastline since it can be drawn to only one set of grid points.

Hansen's model has been tested in areas with one open boundary, such as Chesapeake Bay, with opposing open boundaries, for the Straits of Gibraltar, and in the "along the coast" problem, for the area from Santa Barbara to San Diego, California. This model for the Gulf of Maine uses two adjacent open boundaries and is an extension of the testing of the model to this new mode.

The FORTRAN II program is shown in the flow chart in Figure 3. The main program consists of one program control, five principal subroutines, and three plotting subroutines. The main program control calls the various subroutines when they are needed and stops the program when it is completed.

The program starts by reading in all initial data, in subroutine J02, with the exception of tidal data at the input boundary. This subroutine also computes the value of all compound parameters used in the program and finally, prints out the input data that was read in as a check on the accuracy of these data. This information is stored in plotting subroutine D01.

Then subroutine J04 prints the computed horizontal fields of water elevation, current magnitude and current direction at the desired time intervals. These values are then stored in plotting subroutine D02.

Subroutine J05 performs the main computations required in the model. It averages and smoothes the u, v, and z values. It computes the actual u, v, and z values at each step. It calls the wind current subroutine. The wind current subroutine, S01, reads in the values of the wind fields. In the integrated equation wind currents are assumed to reach the bottom in shallow beach areas, and to extend downward to the top of the thermocline in regions of deep water.

The dotted lines represent a second sequence of printing out the computed values by J04 and the storage of these values for future plotting by subroutine D02. The program then proceeds to compute the values for the special points in subroutine S08. The program ends by storing this information in plotting subroutine D03.

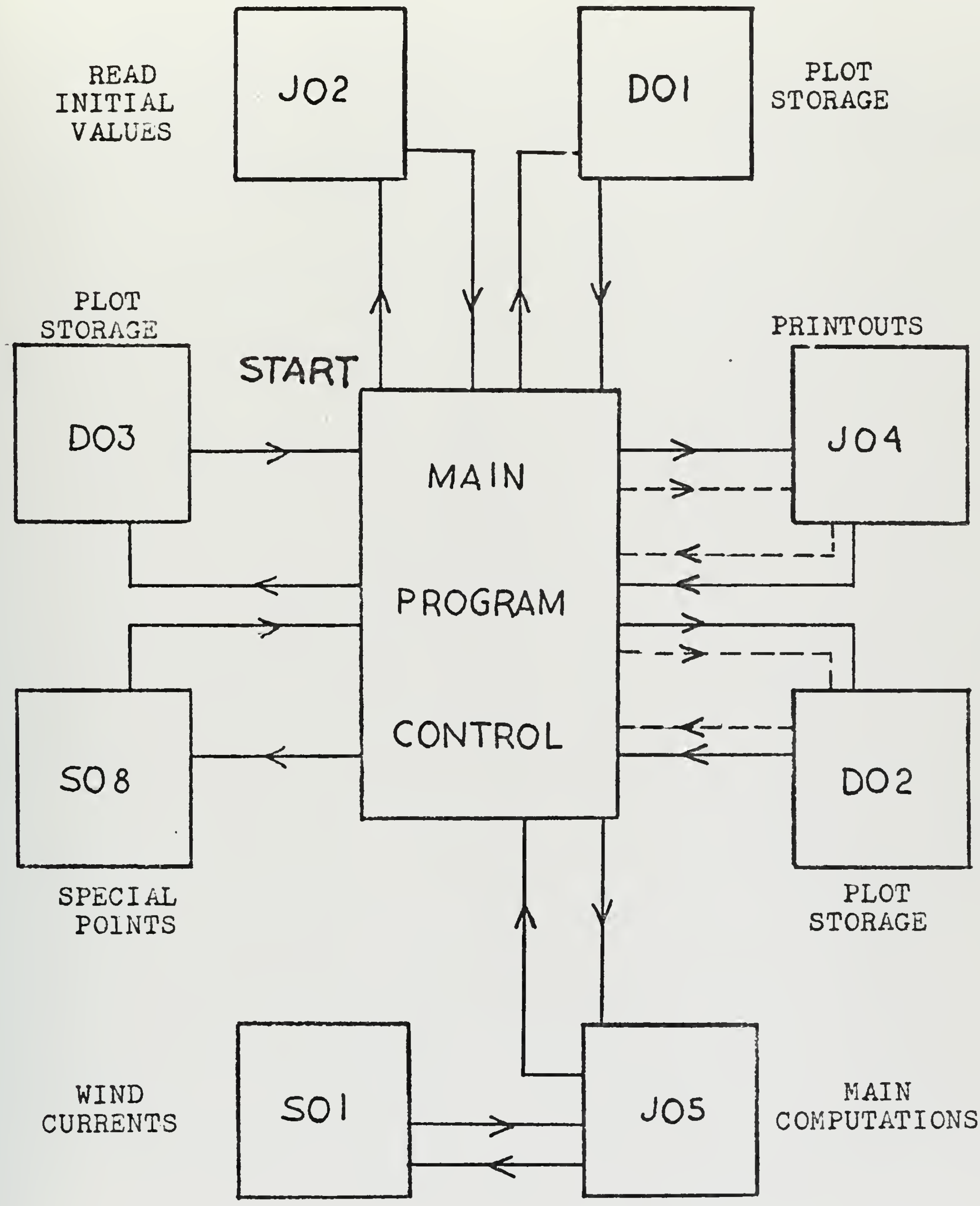

FIGURE 3 FLOW CHART

The information from the three plotting subroutines is then stored on a magnetic tape which in turn serves as the input to a separate plotting program.

Appendix A contains an identification of the symbols used in this program.

IV. THE INPUT DATA

The first parameter chosen is the grid size. The size selected depends on the area of study, the detail desired, and the available computer core storage memory. The large area of the Gulf of Maine makes the use of a large array computer, the CDC 6500, necessary. The grid size of six nautical miles used in this study requires 225,000 bytes of core memory to run the entire program. This is over one-half the available memory of the computer. A smaller grid size, of say three nautical miles, requires even more memory. Because of rough topography a larger grid size results in a less accurate reproduction of the tides and tidal currents due to over smoothing of the depth distribution.

The selection of a grid size fixes the size of the computation array. A six nautical mile grid size used in an area five degrees of latitude by five degrees of longitude means the computational grid array will be 51 x 51 units. The number of points on each open boundary is fixed by the geography along the boundary. In this region both open boundaries contain only points located over water. Each open boundary then contains 51 points.

The selection of the special points; at which the effects of wind on tidal height, speed, and direction are studied, is based on many factors. The principal reason is the interest value of the point. Any of the

approximately 2,000 grid points located over water are suitable for selection. The points chosen for this model are: the open sea outside Boston, Massachusetts, the center of Cape Cod Bay, the center of Buzzards Bay on the western side of the Cape Cod Canal, the river mouth near Portsmouth, New Hampshire, the indented coast near Portland, Maine, the port of Rockland, Maine, Bar Harbor, Maine, the center of the Grand Manan Channel, a point in the center of Wilkinson Basin, the channel between Nantucket and Chappaquidick Islands, a point seaward of Cape Cod , a point over the continental slope, two points in the region of Nantucket Shoals, and finally a point south of Grand Manan Island over the continental shelf. These points are shown in Figures 8, 9, and 10.

Each type of topography, water depth, and coastal location is represented by one of these special points. The objective is to describe the region by comparison and contrast at the various special locations.

The acceleration of gravity is 980.665 cm/sec^2 for this problem. This is a widely accepted value for gravity.

The program provides two parameters for computing the wind effects on the tides and tidal currents from a given barometric pressure distribution. These parameters are the coefficient of geostrophic wind, 0.65, and the average air density given by 1.1627×10^{-3} gm/cm^3. These parameters do not enter into the program when uniform

wind fields are used. This model uses uniform wind fields.

The program provides the option of using four separate tidal constituents at each open boundary or of using only the velocity of the M2 tide at these same boundaries. This model uses four separate tidal constituents at each open boundary.

The coriolis parameter used is given as 9.5620×10^{-5} sec^{-1}. This is an average for the latitude of the region.

The coefficient of bottom friction, the proportionality factor between the wind stress and square of the wind velocity, and the smoothing parameter used with the coefficient of horizontal eddy diffusivity are given by values which Hansen found to be the most suitable after much experimentation with the model for widely separate bodies of water. The coefficient of friction used in this study is 0.003. This as a dimensionless parameter. The components of the wind stress and the square of the wind velocity are related by the proportionality factor 3.2×10^{-6}. The numerical smoothing parameter, a, is 0.998. Hansen obtained the most accurate results with his model using these values.

The one-half space step is determined by the grid size. In this problem it is given as 5.5506×10^{5} centimeters, or three nautical miles. The maximum length of the time step is determined from the maximum grid size

and depth in the area according to the Courant-Friedrich-Levy criterion.

$$t \leq \frac{2\ell}{(g H_{max})^{1/2}} \tag{20}$$

In this formula, t is the time in seconds, ℓ the grid size in centimeters, g the acceleration of gravity, and H_{max} the maximum depth in the area of computation in centimeters. When this criterion is applied to the Gulf of Maine, a time step of 31 seconds results.

The wind field characteristics are determined by the programmer. The wind fields are specified by the wind velocity in m/sec, the wind direction computation co-ordinates, and the time, in seconds, when the wind starts blowing. The wind fields constitute one of the two primary inputs to the program. Their values are introduced at each grid point for every time step throughout the program.

The tidal constituents are obtained from tabulated values for various locations throughout the world. The M2, K1, S2, and N2 constituents for Grand Manan Island are used for the eastern open boundary and the M2, K1, S2, and N2 constituents for the western end of the Cape Cod Canal are used for the southern open boundary. These values are introduced at each respective open boundary point for every time step throughout the program. Table I summarizes the values of the tidal constituents used.

TABLE I

Constituent	Grand Manan Island Speed (cm/sec)	Grand Manan Island Direction °T	W. Cape Cod Canal Speed (cm/sec)	W. Cape Cod Canal Direction °T
M2	251.5	339	50.0	230
S2	39.0	015	10.0	275
K1	13.7	131	10.0	080
N2	49.4	312	15.0	205

The final data decisions are those concerning how many runs to make and the various time considerations involved with each run. A total of seven separate runs are reported in this thesis. The first is a run using only the tidal inputs and no wind. This run requires a total of approximately five hours of computer time on the CDC 6500 to accomplish thirty-five hours of computations. This is sufficient to cover almost three semi-diurnal tidal cycles and to establish the tidal circulation.

The next four data runs use 20 knot wind fields from the four cardinal directions. In each case the wind is introduced at the five hour mark and terminated at thirty-five hours. Output from the model is obtained at two hour intervals. The objective is to combine the wind and tidal circulation and see how the wind fields modify the tides and tidal currents.

The final two data runs use the same format for length of computation, introduction of the wind, and

termination of the wind. The velocity is increased to 30 knots and the directions are altered from the southeast and northeast respectively. The input parameters and their data card format and arrangement are contained in Appendix B

V. RESULTS

The results of this study consist of a computer output for each of the seven data runs. Each computer printout contains the water elevation in centimeters, the resultant tidal current speed in centimeters per second, and the tidal current direction in degrees true for each grid point at two hour intervals. Each run contains nineteen such printouts. The same information is printed out for each of the fifteen special points.

This produces a great deal of data. Each two hourly printout of values contains computed information for nearly two thousand oceanic grid points. It is difficult to interpret all of this information without some reasonably detailed plots. The ideal situation is to develope a computer program to plot part or all of the data manually in some suitable format. Because of difficulty with the plot program and time limitations the alternative of plotting part of the data is necessary.

The results are discussed in two sections. The first section concerns the verification of the Hansen model in the Gulf of Maine. The second section discusses the effects of various wind speeds and directions on the tidal water level, tidal current speed, and the tidal current direction.

A. VERIFICATION OF THE HANSEN MODEL

The verification of the model requires that some observed data be compared with the numerical values obtained from the model. The observed data used in this instance is tidal current data compiled by the U. S. Coast and Geodedic Survey. This data represents current measurements extracted from light ship observations over a period of several years. The currents are not correlated with the winds present at the times that they were measured. This means that the comparison of data that follows actually compares average currents produced over a period of years by widely varying atmospheric conditions with the instantaneous values produced by the model for a unique set of prevailing conditions.

Figure 4 presents tidal current speed in knots and tidal current direction as indicated by the vectors, for the observed Coast and Geodedic Survey data. This description pertains to the time of five minutes after low water at Boston, Massachusetts. Immediately beneath this data, Figure 5 presents the same information obtained from the model for the same approximate locations and time of low water at Boston, Massachusetts. In extracting comparison information from the model, the closest grid point to the location of the observed data is used. The measurements are not compared at exactly the same geographic location. Figures 6 and 7 perform the same respective functions for the high tide situation.

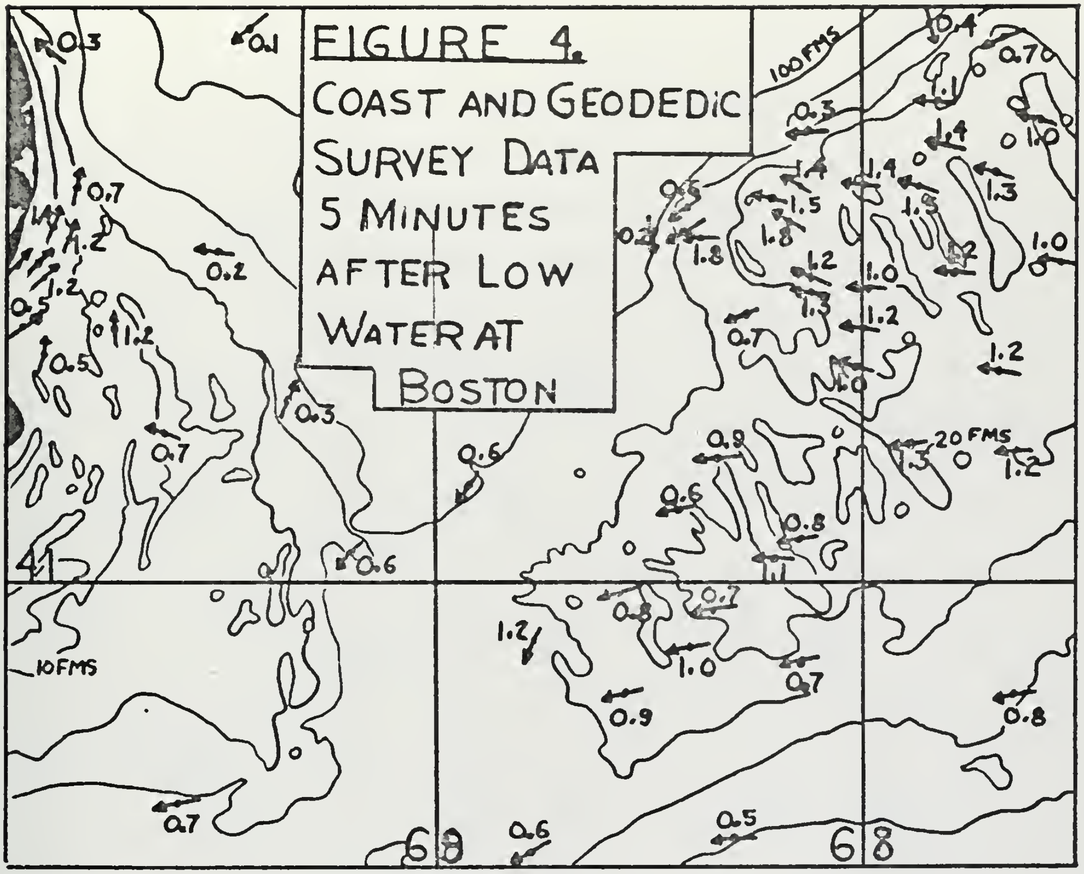

FIGURE 4.
COAST AND GEODEDIC SURVEY DATA
5 MINUTES AFTER LOW WATER AT BOSTON

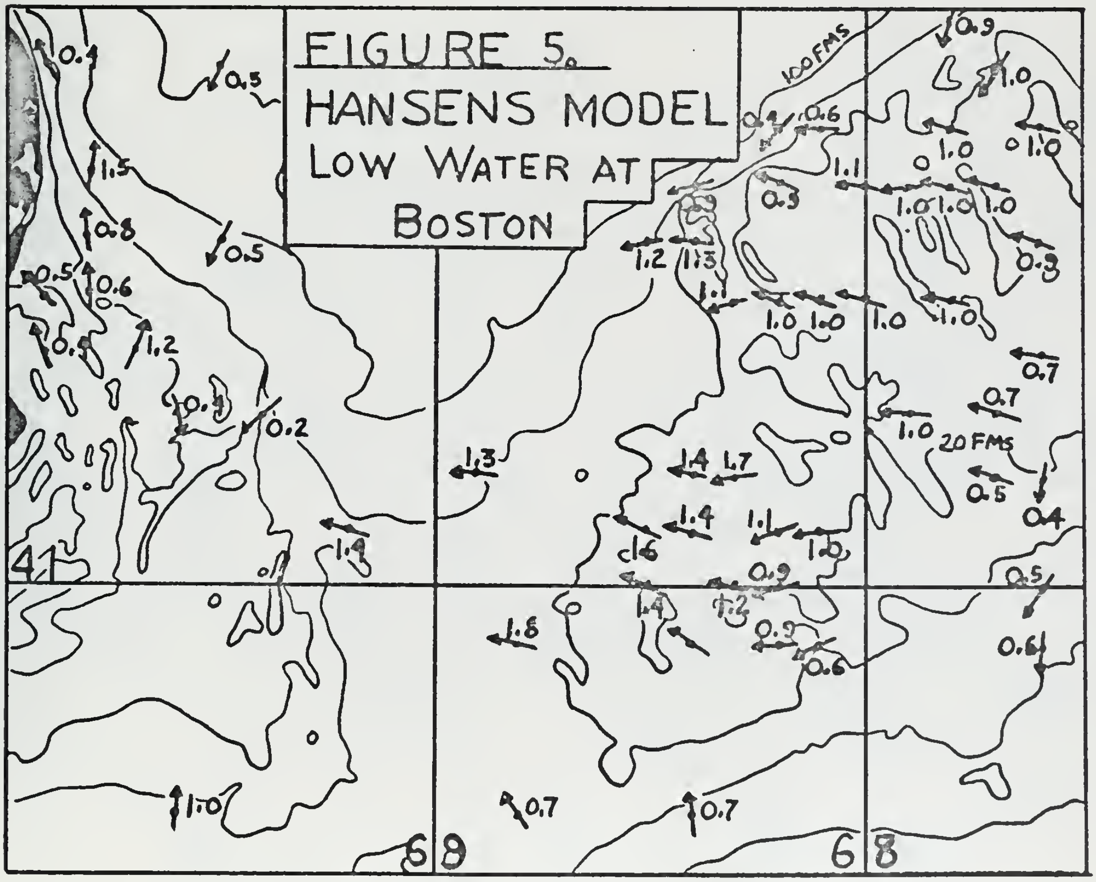

FIGURE 5.
HANSENS MODEL
LOW WATER AT BOSTON

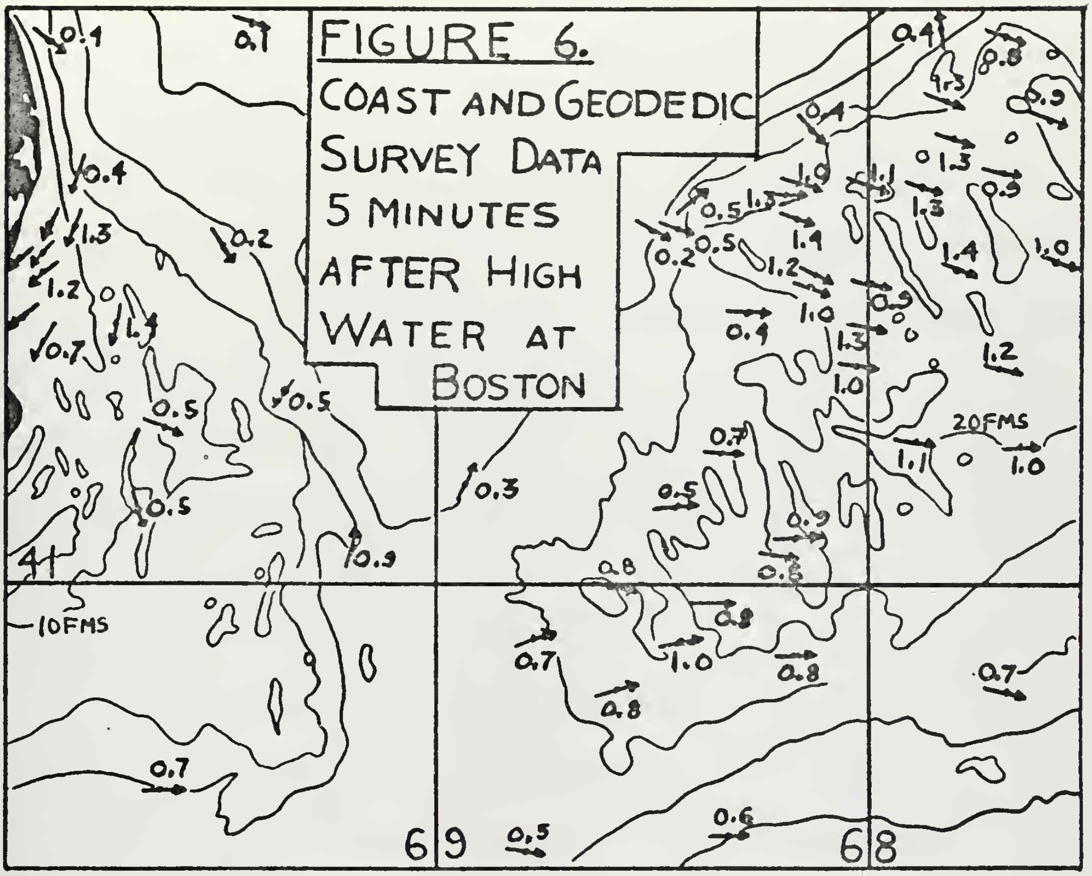

FIGURE 6.
COAST AND GEODEDIC SURVEY DATA 5 MINUTES AFTER HIGH WATER AT BOSTON

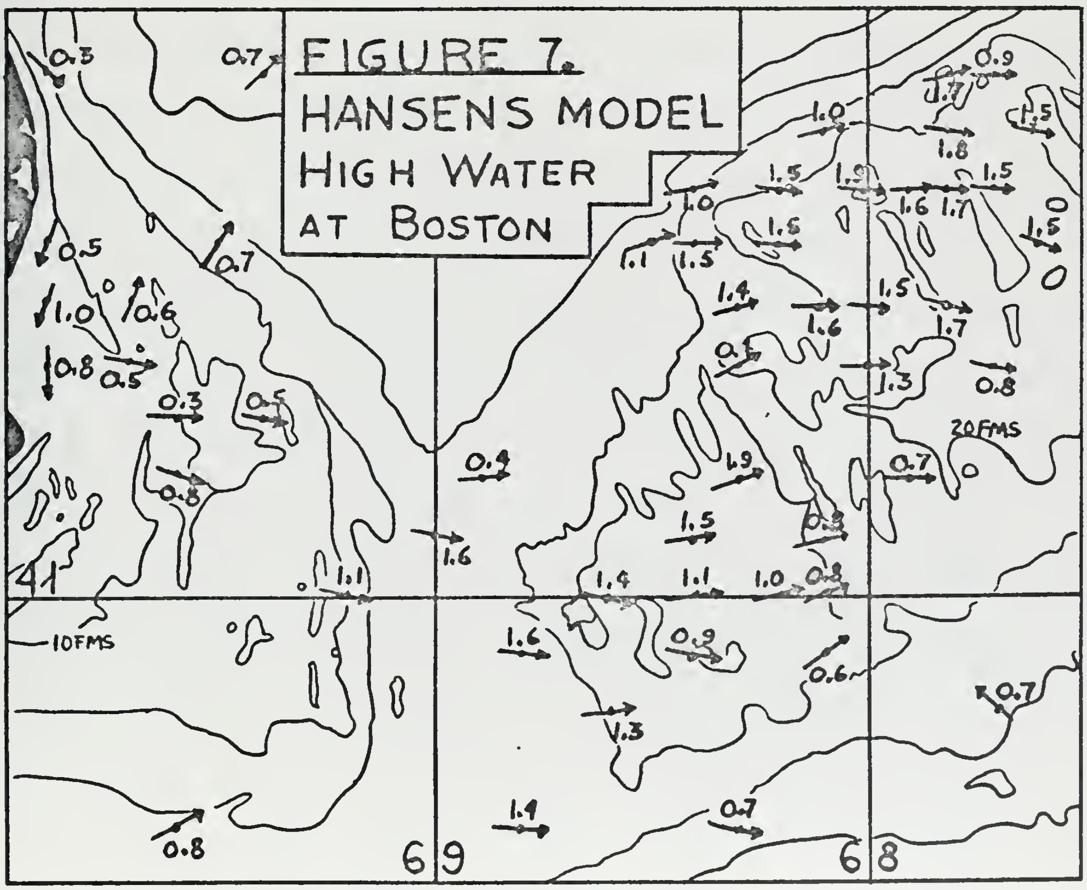

FIGURE 7.
HANSENS MODEL HIGH WATER AT BOSTON

Comparison of these figures shows broad subjective agreement between the observed data and that computed by Hansen's model for the high and low tide situations. The agreement shown is general and not in detail. In fact, there are specific points at high and at low tide where disagreement is evident. The tidal speeds do show an order of magnitude agreement. The directions of the tidal currents appear reasonable for both high and low tide. The agreement shown suggests that currents in the region are probably tidally dominated.

The information used in Figures 5 and 7 is obtained from the no wind run of the model. The reference station used is Boston, Massachusetts to conform with the Coast and Geodedic Survey data.

The region of comparison is known as George's Bank and covers an area bounded by latitude 40°30'N and 42°N and between 67°30'W and 70°W longitude. This represents only a portion of the entire Gulf of Maine area.

The meteorological conditions prevailing in the Gulf of Maine vary considerably from month to month. There is a noticeable difference in the pattern of the mean wind flow between winter and summer. In February, a month typical of the winter regime, the mean winds are westerly with a velocity ranging from 7 to 27 knots. The summer season, represented by August, has mean winds that are predominant by southerly to southeasterly with velocities from 3 to 16 knots. The Gulf of Maine is a

region of cyclonic storm activity and exhibits a wide range of wind speeds and directions during any given period.

The verification if somewhat disappointing in that many questions remain unresolved. The principal obstacle remains ascertaining the conditions prevailing when the observed data was recorded by the Coast and Geodedic Survey. Unfortunately, the data does not provide the meteorological conditions prevailing at the time the measurements were made. Since they are averages obtained over many years it is assumed that many separate wind fields prevailed during these current measurements. This appears to preclude a more accurate verification without additional specific information.

Figure 8 presents the tidal current circulation in the Gulf of Maine when high tide occurs at Boston, Massachusetts. Figures 9 and 10 show the same information for slack water and low tide respectively. Slack water and a zero tide level occur almost simultaneously for this location. All three diagrams are compiled from the no wind data run and show tidal circulation not driven by any specific wind.

B. THE EFFECT OF WIND FIELDS ON TIDAL HEIGHT, TIDAL CURRENT SPEED AND TIDAL CURRENT DIRECTION

The effect of the various wind fields on the tides and tidal current circulation is presented in a series of

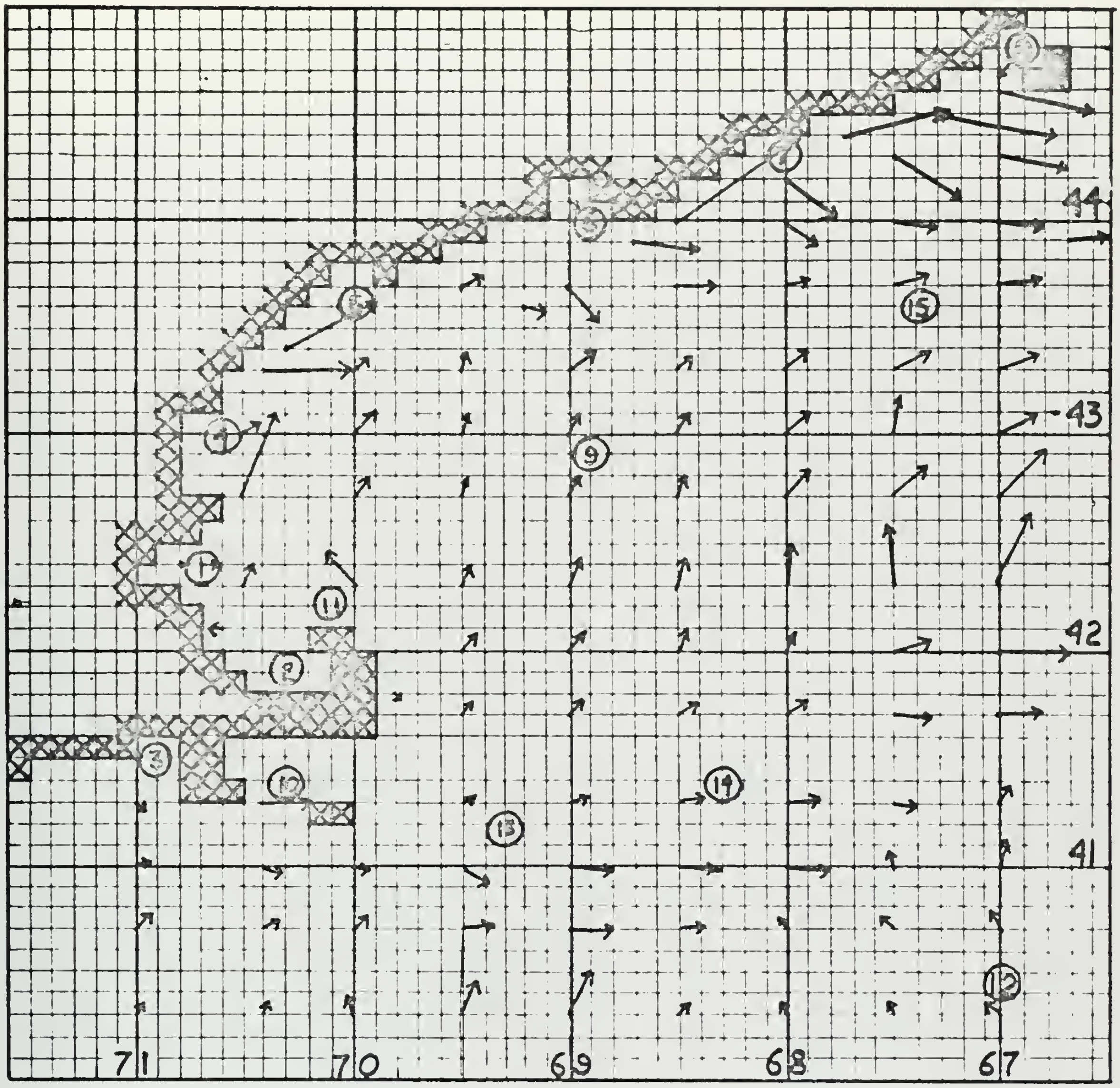

FIGURE 8 GULF OF MAINE HIGH WATER AT BOSTON

① BOSTON, MASS.
② E. CAPE COD CANAL
③ NEW BEDFORD, MASS.
④ PORTSMOUTH, N. H.
⑤ PORTLAND, ME.
⑥ ROCKLAND, ME.
⑦ BAR HARBOR, ME.
⑧ GRAND MANAN IS.
⑨ CASHES LEDGE
⑩ CHAPPAQUIDICK IS.
⑪ PROVINCETOWN, MASS.
⑫ CONTINENTAL SLOPE
⑬ NANTUCKET SHOALS
⑭ GREAT SOUTH SHOALS
⑮ SEAWARD OF GRAND MANAN ISLAND

SCALE (CM/SEC)

→ < 50
→ 50-100
→ 100-150
→ 150-200
→ 200-250
→ >250

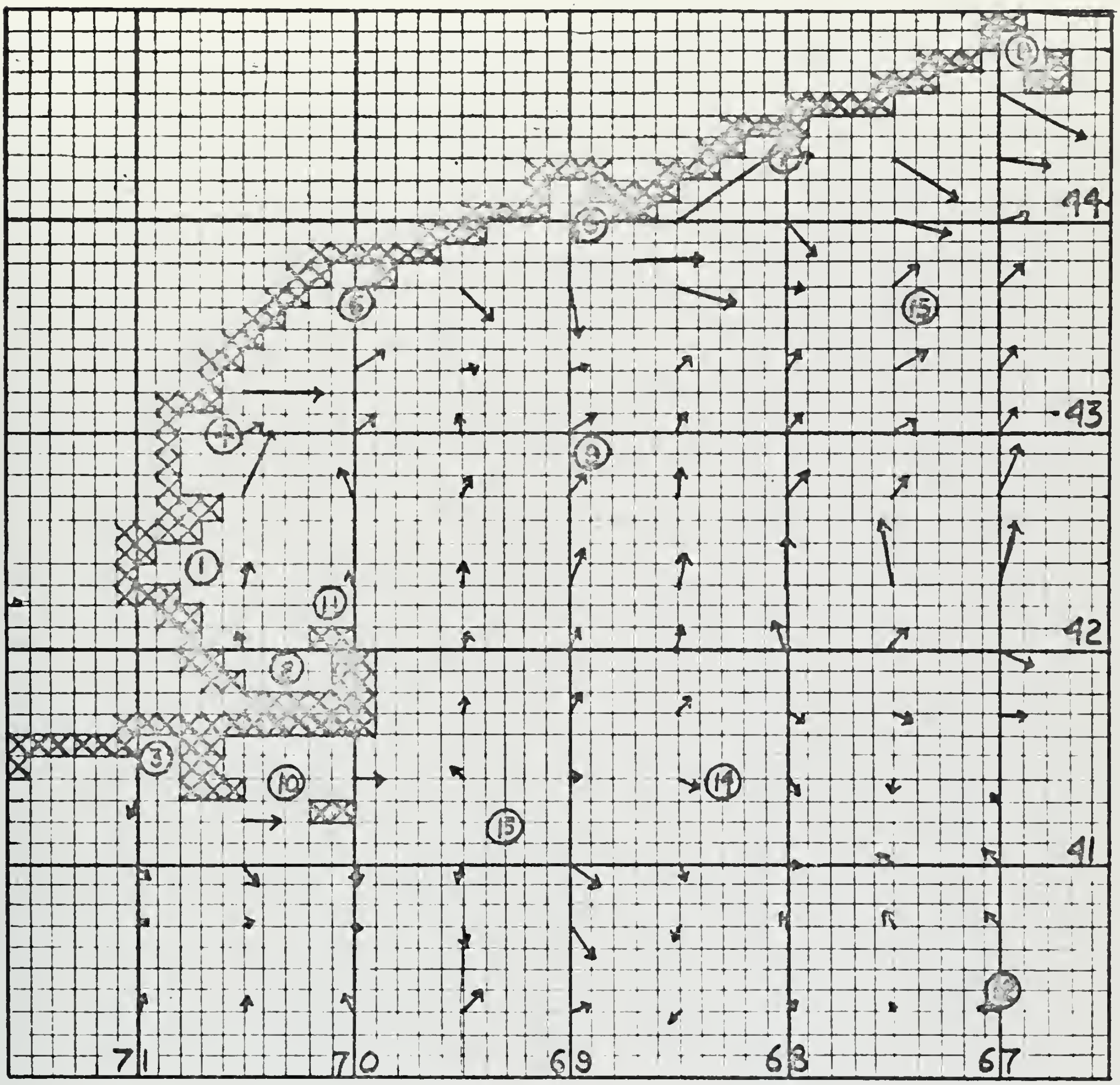

FIGURE 9 GULF OF MAINE SLACK WATER AT BOSTON

① BOSTON, MASS.
② E. CAPE COD CANAL
③ NEW BEDFORD, MASS.
④ PORTSMOUTH, N. H.
⑤ PORTLAND, ME.
⑥ ROCKLAND, ME.
⑦ BAR HARBOR, ME.
⑧ GRAND MANAN IS.
⑨ CASHES LEDGE
⑩ CHAPPAQUIDICK IS.
⑪ PROVINCETOWN, MASS.
⑫ CONTINENTAL SLOPE
⑬ NANTUCKET SHOALS
⑭ GREAT SOUTH SHOALS
⑮ SEAWARD OF GRAND MANAN ISLAND

SCALE (CM/SEC)

→	<50
→	50-100
→	100-150
→	150-200
→	200-250
→	>250

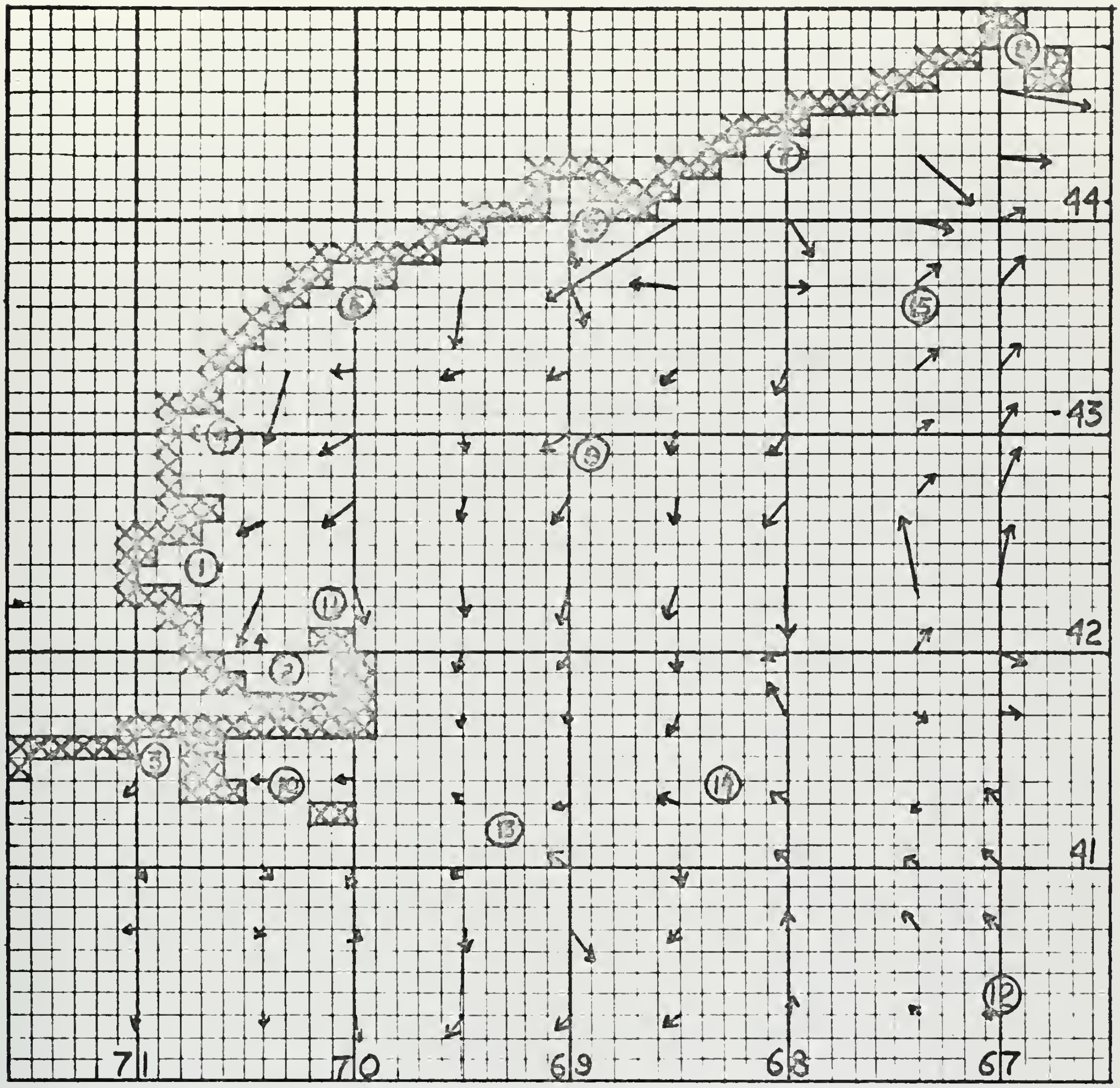

FIGURE 10 — GULF OF MAINE — LOW WATER AT BOSTON

① BOSTON, MASS.
② E. CAPE COD CANAL
③ NEW BEDFORD, MASS.
④ PORTSMOUTH, N. H.
⑤ PORTLAND, ME.
⑥ ROCKLAND, ME.
⑦ BAR HARBOR, ME.
⑧ GRAND MANAN IS.
⑨ CASHES LEDGE
⑩ CHAPPAQUIDICK IS.
⑪ PROVINCETOWN, MASS.
⑫ CONTINENTAL SLOPE
⑬ NANTUCKET SHOALS
⑭ GREAT SOUTH SHOALS
⑮ SEAWARD OF GRAND MANAN ISLAND

SCALE (CM/SEC)

→ < 50   ⟶ 100–150   ⟶ 200–250

→ 50–100   ⟶ 150–200   ⟶ > 250

tables. The values used are those computed for the fifteen special points for each of the seven data runs.

The duration of the wind is considered by choosing times such that the fully arisen sea and non-fully arisen sea cases are considered. The wind is introduced at the five hour point in each data run. The first time chosen is at 10 hours or five hours after the wind starts. Five hours is not sufficient time for a twenty or thirty knot wind to build into a fully arisen sea (i.e. time for the energy content of the sea to be saturated). The second selected time is at 24 hours or 19 hours after the onset of the wind. This time frame is sufficient for the 20 knot winds to generate a fully arisen sea but not for the 30 knot winds to accomplish the same result. The final time selected is at 35 hours or 30 hours after the onset of the wind. This allows the 30 knot winds to generate a fully arisen sea and explores the effects of allowing the wind to blow over an already fully arisen sea for eleven hours in the case of the 20 knot wind fields.

The water elevation after 10 hours, (5 hours of wind) is summarized for the fifteen special points in Table II. Similar information for 24 hours and for 35 hours of wind is contained in Tables III and IV respectively. Table V contains the maximum change in water height produced by any wind field at each point for times ten, twenty-four, and thirty-five hours. The range of maximum wind produced changes runs from no change at New Bedford, Massachusetts

TABLE II

LOCATION	WATER ELEVATION (CM) AT TIME 10 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE. WIND	30 KNOT NE. WIND
BOSTON,MASS.	5.88	6.93	3.93	3.14	8.39	3.23	-1.69
CAPE COD BAY	3.44	4.37	1.96	3.14	3.52	4.49	0.72
NEW BEDFORD,MASS	0.20	0.20	0.20	0.20	0.20	0.20	0.20
PORTSMOUTH,N.H.	-56.26	-56.52	-55.91	-62.43	-50.38	-66.64	-65.33
PORTLAND,ME.	-79.32	-80.36	-78.33	-86.84	-71.65	-92.71	-89.97
ROCKLAND,ME.	-5.34	-4.01	-7.06	-5.09	-4.78	-3.83	-8.03
BAR HARBOR,ME.	-87.20	-88.10	-86.29	-92.68	-81.79	-97.31	-94.55
GRAND MANAN IS.	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CASHES LEDGE	-77.54	-77.28	-77.86	-80.70	-74.52	-82.00	-83.36
CHAPPAQUIDICK IS.	-11.76	-13.94	-12.38	-20.47	-8.50	-29.48	-23.93
PROVINCETOWN,MASS.	-12.67	-11.99	-13.70	-15.27	-10.22	-15.65	-18.62
CONTINENTAL SLOPE	-84.48	-84.39	-84.57	-85.36	-83.64	-85.75	-86.01
NANTUCKET SHOALS	-63.79	-64.76	-63.18	-66.17	-62.86	-69.17	-67.91
GREAT SOUTH SHOALS	-79.78	-79.46	-80.12	-81.46	-78.16	-81.86	-83.14
GR. MANAN CHANNEL	-155.02	-154.98	-155.04	-156.30	-153.72	-156.98	-157.10

TABLE III

LOCATION	WATER ELEVATION (CM) AT TIME 24 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE.WIND	30 KNOT NE.WIND
BOSTON,MASS.	-0.24	1.36	-2.51	-1.59	0.70	0.07	-5.89
CAPE COD BAY	-0.24	-0.32	-0.76	0.56	-1.23	1.72	-0.11
NEW BEDFORD,MASS.	0.20	0.20	0.20	0.20	0.20	0.20	0.20
PORTSMOUTH,N.H.	-24.37	-22.84	-26.28	-31.04	-17.97	-32.42	-37.90
PORTLAND,ME.	-43.70	-42.75	-44.53	-49.11	-38.44	-51.02	-53.67
ROCKLAND,ME.	-1.04	-0.41	-2.73	-1.22	-0.48	-1.01	-4.12
BAR HARBOR,ME.	-88.24	-88.63	-87.69	-92.18	-84.19	-95.57	-93.79
GRAND MANAN IS.	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CASHES LEDGE	-74.90	-73.98	-75.87	-76.98	-72.81	-76.70	-79.60
CHAPPAQUIDICK IS.	-1.87	-4.41	-2.29	-11.54	4.45	-20.33	-13.04
PROVINCETOWN,MASS.	-15.50	-14.93	-16.19	-16.42	-14.62	-15.90	-18.11
CONTINENTAL SLOPE	-24.03	-24.07	-24.03	-25.12	-22.98	-25.79	-25.72
NANTUCKET SHOALS	-11.58	-9.29	-12.58	-13.00	-9.54	-10.45	-17.02
GREAT SOUTH SHOALS	-29.95	-29.32	-30.52	-31.34	-29.15	-30.92	-34.03
GR. MANAN CHANNEL	-139.12	-138.99	-139.22	-140.41	-137.76	-140.87	-141.39

TABLE IV

LOCATION	WATER ELEVATION (CM) AT TIME 35 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE. WIND	30 KNOT NE. WIND
BOSTON, MASS.	1.04	2.93	-0.79	0.56	1.41	2.71	-3.31
CAPE COD BAY	0.80	0.93	0.82	1.85	-0.30	3.30	1.98
NEW BEDFORD, MASS.	0.20	0.20	0.20	0.20	0.20	0.20	0.20
PORTSMOUTH, N.H.	-9.02	-7.73	-10.51	-14.44	-3.79	-15.48	-20.50
PORTLAND, ME.	-16.03	-14.91	-17.09	-20.78	-11.46	-22.02	-25.38
ROCKLAND, ME.	0.48	1.36	-0.64	0.27	1.30	0.67	-1.52
BAR HARBOR, ME.	-40.76	-41.09	-40.39	-44.72	-36.96	-47.51	-46.61
GRAND MANAN IS.	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CASHES LEDGE	-42.99	-41.90	-43.98	-44.16	-41.83	-43.21	-46.43
CHAPPAQUIDICK IS.	0.83	0.66	1.61	-6.45	7.95	-13.24	-6.69
PROVINCETOWN, MASS.	-6.53	-6.17	-6.53	-6.77	-6.06	-6.28	-7.28
CONTINENTAL SLOPE	35.70	35.71	35.67	34.54	36.84	33.88	33.80
NANTUCKET SHOALS	2.44	4.11	0.80	2.44	2.63	7.07	-1.24
GREAT SOUTH SHOALS	5.40	7.14	4.20	5.35	5.72	7.27	2.84
GR. MANAN CHANNEL	-74.07	-73.50	-74.51	-74.85	-73.34	-74.55	-76.00

TABLE V			
LOCATION	MAXIMUM CHANGE IN WATER ELEVATION (CM)		
	10 HOURS	24 HOURS	35 HOURS
BOSTON, MASS.	7.57	5.65	4.35
CAPE COD BAY	2.72	1.96	2.50
NEW BEDFORD, MASS.	0.00	0.00	0.00
PORTSMOUTH, N.H.	10.38	13.53	11.48
PORTLAND, ME.	13.39	9.97	9.35
ROCKLAND, ME.	2.69	2.92	2.00
BAR HARBOR, ME.	7.35	7.33	6.75
GRAND MANAN IS.	0.00	0.00	0.00
CASHES LEDGE	5.82	4.70	3.44
CHAPPAQUIDICK IS.	17.72	18.46	7.52
PROVINCETOWN, MASS.	5.95	2.51	0.75
CONTINENTAL SLOPE	1.53	1.76	1.90
NANTUCKET SHOALS	5.38	5.44	4.63
GREAT SOUTH SHOALS	3.36	4.08	2.56
GR. MANAN CHANNEL	2.08	2.27	1.93

and Grand Manan Island to a change of 18.46 centimeters for Chappaquidick Island at the 24 hour time. The greatest change in tidal height due to any wind field amounts to 18.46 centimeters or approximately one half a foot for the locations and conditions specified in this study. In computing the differences reported in Table V, the no wind data from Tables II, III, and IV serves as the base or reference data. No attempt is made to identify the wind field responsible for producing the greatest change at each point.

The changes at deep water locations are small while the greatest changes in tidal height induced by the wind occur at points in relatively shallow water. This may be a consequence of the averaging of the model equations over depth. The lack of any change at New Bedford, Massachusetts is attributed to the effects of geography. This location is sheltered by boundary points from every wind field used in this study. The maximum changes observed do not necessarily occur when the wind has been blowing for its full duration.

The effects of the various wind fields on the tidal current speed and direction at the special points are presented in Tables VI, VII, and VIII for the ten, twenty-four, and thirty-five hour times. A summary of the maximum changes in these quantities is presented in Table IX. Once again only the greatest changes are considered

TABLE VI

LOCATION	TIDAL CURRENT MAGNITUDE (CM/SEC)/DIRECTION (°T) AT TIME 10 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE.WIND	30 KNOT NE.WIND
BOSTON,MASS.	31/339	23/032	51/320	49/345	12/283	49/021	80/327
CAPE COD BAY	31/336	21/023	48/321	40/347	25/312	40/042	65/328
NEW BEDFORD,MASS.	42/102	61/104	20/083	51/070	48/130	77/079	41/024
PORTSMOUTH,N.H.	64/003	65/008	64/357	76/359	49/008	82/004	83/351
PORTLAND,ME.	130/038	132/039	128/037	139/036	120/042	147/036	141/033
ROCKLAND,ME.	25/134	35/136	8/154	27/077	37/163	45/078	37/011
BAR HARBOR,ME.	169/026	171/027	167/025	176/024	162/028	183/024	177/021
GRAND MANAN IS.	0/999	0/999	0/999	0/999	0/999	0/999	0/999
CASHES LEDGE	51/051	51/054	51/049	53/051	48/052	54/054	54/046
CHAPPAQUIDICK IS.	41/058	52/067	29/031	58/034	38/131	76/040	60/007
PROVINCETOWN,MASS.	123/326	115/328	131/324	130/327	117/325	121/330	146/324
CONTINENTAL SLOPE	33/313	33/314	33/313	29/308	37/318	27/305	27/302
NANTUCKET SHOALS	48/111	56/112	38/108	52/096	46/129	55/122	43/077
GREAT SOUTH SHOALS	76/072	80/074	72/069	80/071	71/073	83/081	77/066
GR. MANAN CHANNEL	76/069	77/070	76/067	77/069	76/069	75/073	77/066

TABLE VII

LOCATION	TIDAL CURRENT MAGNITUDE (CM/SEC)/DIRECTION (°T) AT TIME 24 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE.WIND	30 KNOT NE.WIND
BOSTON,MASS.	6/046	32/125	38/318	29/013	22/197	42/067	66/328
CAPE COD BAY	8/010	17/119	30/321	19/053	17/290	40/104	42/339
NEW BEDFORD,MASS.	12/136	37/113	29/292	34/054	29/191	60/073	45/333
PORTSMOUTH,N.H.	47/014	47/022	47/005	61/006	27/034	68/012	70/355
PORTLAND,ME.	104/046	104/047	104/044	113/042	94/051	119/042	118/037
ROCKLAND,ME.	19/154	31/136	7/260	20/067	36/177	39/075	38/355
BAR HARBOR,ME.	163/024	165/025	161/023	168/022	157/126	174/023	169/019
GRAND MANAN IS.	0/999	0/999	0/999	0/999	0/999	0/999	0/999
CASHES LEDGE	49/056	48/060	50/053	51/056	47/056	51/062	55/051
CHAPPAQUIDICK IS.	22/051	31/068	20/338	47/019	36/174	65/031	54/351
PROVINCETOWN,MASS.	102/331	91/333	112/330	106/333	98/330	91/338	125/331
CONTINENTAL SLOPE	30/321	30/321	30/321	20/300	41/331	17/276	17/279
NANTUCKET SHOALS	31/181	38/162	25/206	29/157	36/199	44/135	7/175
GREAT SOUTH SHOALS	44/087	44/093	44/080	49/084	36/089	44/135	51/074
GR. MANAN CHANNEL	62/056	61/058	63/055	63/057	62/056	62/059	64/054

TABLE VIII

LOCATION	TIDAL CURRENTS MAGNITUDE (CM/SEC)/DIRECTION (°T) AT TIME 35 HOURS						
	NO WIND	20 KNOT S. WIND	20 KNOT N. WIND	20 KNOT E. WIND	20 KNOT W. WIND	30 KNOT SE. WIND	30 KNOT NE. WIND
BOSTON, MASS.	11/145	39/134	29/310	22/040	26/189	43/089	57/328
CAPE COD BAY	7/137	26/133	16/311	20/101	13/251	48/116	25/354
NEW BEDFORD, MASS	5/252	31/115	34/292	29/037	31/218	55/068	48/326
PORTSMOUTH, N.H.	31/027	32/040	31/011	49/012	27/151	57/019	59/356
PORTLAND, ME.	69/054	69/058	69/051	81/046	55/072	88/045	88/038
ROCKLAND, ME.	18/194	27/155	20/271	15/035	38/197	34/070	41/339
BAR HARBOR, ME.	114/027	116/029	112/025	122/024	105/031	129/025	124/019
GRAND MANAN IS.	0/999	0/999	0/999	0/999	0/999	0/999	0/999
CASHES LEDGE	36/068	36/074	37/063	39/067	34/069	39/074	42/059
CHAPPAQUIDICK IS.	7/185	20/119	21/281	40/008	42/189	56/027	50/341
PROVINCETOWN, MASS.	62/343	50/352	72/338	66/346	59/340	52/006	87/340
CONTINENTAL SLOPE	15/329	15/329	16/330	7/250	30/347	14/206	13/209
NANTUCKET SHOALS	17/260	17/199	26/297	7/260	26/267	23/135	28/329
GREAT SOUTH SHOALS	12/103	14/135	13/073	18/095	7/121	23/112	22/067
GR. MANAN CHANNEL	40/043	39/045	41/040	41/043	40/042	40/048	43/040

TABLE IX

LOCATION	MAXIMUM CHANGE IN TIDAL CURRENT MAGNITUDE (CM/SEC) TIDAL CURRENT DIRECTION (°T)		
	10 HOURS	24 HOURS	35 HOURS
BOSTON, MASS.	49/53	60/151	46/165
CAPE COD BAY	34/66	34/109	41/174
NEW BEDFORD, MASS.	35/78	48/158	50/176
PORTSMOUTH, N.H.	19/12	23/20	28/124
PORTLAND, ME.	17/5	15/9	19/18
ROCKLAND, ME.	20/123	20/159	23/159
BAR HARBOR, ME.	14/5	11/5	15/15
GRAND MANAN IS.	0/0	0/0	0/0
CASHES LEDGE	3/5	6/6	6/9
CHAPPAQUIDICK IS.	35/73	43/123	49/177
PROVINCETOWN, MASS.	23/4	23/7	25/23
CONTINENTAL SLOPE	4/11	13/45	15/123
NANTUCKET SHOALS	10/34	24/46	11/125
GREAT SOUTH SHOALS	7/9	9/13	11/36
GR. MANAN CHANNEL	1/4	2/3	3/5

and no attempt is made to identify the particular combination of wind speed and direction that causes the greatest change at a given location for a given time.

The variation in tidal current speed runs from a high of 60 cm/sec at Boston, Massachusetts at 24 hours to a low value of only 1 cm/sec in the Grand Manan Channel at the 10 hour point. Thus the range of changes varies from 1/50 of a knot to 1.2 knots in speed.

The variation in the direction of the tidal currents due to the addition of the winds is great. The range is from a very small change of only 2 degrees to an almost complete reversal of direction of 178 degrees.

TABLE X

WIND VELOCITY (KNOTS)	10	20	30	40	50
AVERAGE CURRENT VELOCITY DUE TO WIND AT FOLLOWING LIGHT-SHIP STATIONS					
BOSTON AND BARNEGAT	0.1	0.1	0.2	0.3	0.3
DIAMOND SHOAL (CAPE HATTERAS)	0.5	0.6	0.7	0.8	1.0
ALL OTHER LOCATIONS	0.2	0.3	0.4	0.5	0.6

Tidal current tables published by the U. S. Coast and Geodedic Survey discuss the effect of the wind on tidal current velocity. Table X shows the reported observed differences caused by various wind speeds. These data are based on observations made by lightships during a period of $5\frac{1}{2}$ years. They do not consider the duration of

the wind field and this helps explain the differences between the data reported in Table IX and the observed values shown in this table.

Points located over deep water, such as the Cashes Ledge point, exhibit very little change in tidal current speed or direction due to the effects of wind. The largest response of these quantities to different wind fields is found at points located in shallow water areas. Geographic position again enters into the evaluation of these factors. The largest changes in speed and direction of the tidal currents occur at points near the boundary between the land and sea. Such points as Cape Cod Bay, New Bedford, Massachusetts, Rockland, Maine, and Chappaquidick Island all exhibit large deviations in the direction of the tidal current in response to various wind fields.

The use of equations integrated over depth spreads out the effect of changes at deep water locations over the full depth at those points. All equal amount of change at a point in more shallow water is distributed over a lesser depth. This helps explain the greater changes noted in shallow water locations.

The model also considers that there is no net mass transport perpendicular to the shoreline. This introduces the explanation that tidal currents flowing at the surface are offset by a subsurface or bottom flow in the opposite direction, so that the net mean current as presented by this model is zero.

VI. CONCLUSIONS

The conclusions reported in this study are divided into three major categories. The first concerns the use of Hansen's model in a mode with two adjacent open boundaries and a modified method for handling the topographic input data. The next category is the verification of the data produced by Hansen's model with observed data. The final category concerns the effects of wind fields on the tidal heights, tidal speeds, and tidal current directions in the Gulf of Maine.

The use of Hansen's model with two adjacent open boundaries produces reasonable results for the Gulf of Maine region. The modified grid network used in this study requires minor adjustments in its use but is workable and results in less time and effort expended in coding and key punching topographic data.

Hansen's model may be used in a variety of ways. The fact that the use of the model with adjacent open boundaries produces reasonable results does not mean that these are the best answers possible. The model can be used with one open boundary, various parameters are subject to change, and any combination of wind speed and direction is possible. The verification of the Hansen model reported in this study is only in broad subjective agreement with observed data. The verification is for a given set of conditions which can be altered to produce an entirely different result.

It is sufficient to say that using the Hansen model with adjacent open boundaries produces reasonable results which are in general agreement with some observed data for the Gulf of Maine.

The conclusions concerning the effects of various wind fields on tidal height, tidal current speed, and tidal current direction are limited in scope and are necessarily confined to the fifteen special points used in the study. Any attempt to extend these conclusions to the other points in the Gulf of Maine is unwarranted as each point must be looked at individually.

The effect of the wind fields used in this study on the tidal height at the points in question is slight with the largest change being only one half a foot. The greatest changes are found at points located in shallow water. In contrast the smallest changes are found for points located in deep water. Geographic location appears to be important in considering the effect of wind fields on the height of the tides.

The effect of the wind fields on tidal current velocity at the specified locations used in this thesis varies considerably. The wind speed and direction is found to have less effect at deep water locations than it does at shallow water points. This is expected because the equations used in this study are integrated over depth and hence, the effects of the wind are spread out over a large area in deep water, vice a much smaller area in

shallow water. Physically this is a reasonable result. The speed of the tidal current increased by 1100% amounting to 1.2 knots at Boston, Massachusetts for the greatest change recorded. This may be of significance and indicates that the wind speed and direction does influence tidal current speed.

The effect of wind speed and direction on the resulting direction of the tidal currents is pronounced. The variation is again found to be greater for points located in shallow water than for deep water locations. In some cases, the direction of the tidal current is found to almost completely reverse under the influence of a wind field. This indicates that wind speed and direction can not be ignored in the prediction of tidal current direction.

It is important to realize that the current experienced by an observer at a given point is a summation of the tidal current, wind driven current and any major oceanic current, such as the Gulf Stream, at that point. This study concerns itself entirely with tidal currents and the effects of various wind fields acting on them.

The Hansen model provides a reasonably fast, generally accurate method of predicting tidal current speed and direction, and tidal height for any given uniquely specified conditions. In this regard, there is a great need for data with which to verify the model. Current measurements should be combined with the atmospheric conditions prevailing at the time they are made to enable investigators

to study the complete atmospheric oceanic system of interactions. It appears the model is most useful for storm surge prediction. This is vital information for coastal engineers and residents of coastal areas. The model is capable of producing information for any point specified and hence can assist in filling the void of knowledge for areas where no observed data on tidal height, speed, or direction is recorded.

This project represents only one attempt to study the tides and tidal currents in the Gulf of Maine. As such it only begins to explore a most complex and involved subject.

VII. SUGGESTIONS FOR FUTURE RESEARCH

The Hansen model is capable of many separate modes of operation. Use of the model in the Gulf of Maine region should be continued and the model should be used in as many different modes of operation as feasible in order to find by comparison and contrast that combination of boundary conditions and parameter values that yields the most realistic results for the region.

The modified grid data handling method requires verification. The Hansen model should be run again for the Gulf of Maine with the same parameters using the original method of handling the topographic data. A comparison of results between the two methods should help determine the worth of the modified method of handling these data.

The rugged, fractured topography of the area suggests that a grid size of six nautical miles may be too course. A grid size of three or maybe even two nautical miles may be necessary to bring out more accurate results for the tidal height, tidal current speeds, and tidal current directions in this area. The smaller grid size should eliminate any effects of over smoothing of the depth distribution possibly caused by the six nautical mile grid size. This may require the sub-division of the Gulf of Maine into two or more smaller regions in order to reduce the computer time involved in such efforts.

The investigation of the effects of various wind fields on the tidal heights and tidal currents is worthy of further efforts. This is essentially storm surge prediction and it is of practical interest to mariners, coastal engineers, and many other groups of persons. It could, some day, prevent property damage or even loss of life by adequately predicting the effects of a severe storm.

Constant experimentation with the Hansen model is the only way to discover whether it is in fact valid for all types of water regions. It's use should be extended to as many separate oceanic areas as feasible.

The Hansen model used in this study is limited in the sense that it does not accurately portray the density distribution of the ocean. The recent development and testing of a so-called multi-layer model should help overcome this difficulty. The results of the multi-layer model and this single density Hansen model can someday be compared to determine which most accurately describes the tides and tidal currents in the Gulf of Maine. It may be that for some regions the single density model is sufficiently accurate. In contrast, the multi-layer models may offer significant improvements in the accuracy of reproducing the tides and tidal currents. Much remains to be accomplished before mother nature is duplicated by a deck of computer cards.

APPENDIX A

ABBREVIATIONS AND PARAMETERS USED IN THE PROGRAM

M	grid index (parallel to entrance)
N	grid index (perpendicular to entrance)
Z(N,M)	water elevation (CM)
U(N,M)	U-component of velocity (CM/SEC)
V(N,M)	V-component of velocity (CM/SEC)
RAD(N,M)	resultant current speed (CM/SEC)
ANG(N,M)	angle from geographic north of resultant current speed
QU(N,M)	fields for summation of the U and V components of currents for computation of the rest currents
QV(N,M)	see QU(N,M)
REST(N,M)	average speed of rest current (CM/SEC)
DIR(N,M)	direction of rest current (geographic co-ordinates)
ZM(N,M)	used in J05 as a smoothing intermediate
ZST(N,M)	used in J05 as an averaging intermediate
HTZ(N,M)	water depth at the water elevation (Z) points
HTU(N,M)	water depth at the U-points
HTV(N,M)	water depth at the V-points
HGU(N,M)	actual water depth at the U-points (HGU=HTV+Z)
HGV(N,M)	actual water depth at the V-points (HGV=HTV+Z)
XK(N,M)	U-component of the wind current divided by depth
YK(N,M)	V-component of the wind current divided by depth
A(I)	characteristics of the wind field

A(1)	time when the wind starts (SEC)
A(2)	wind speed (M/SEC)
A(3)	wind direction (computation co-ordinates)
NU(I)	wind field delimeters (N and M co-ordinates of the upper and lower right corners of the wind field)
MU(I)	see NU(I)
NZ(I)	co-ordinates (N,M) of the points used as selected special points
MZ(I)	see NZ(I)
NK(I)	co-ordinates (N,M) of the points on the first open boundary
MK(I)	see NK(I)
NA(I)	co-ordinates (N,M) of the points on the second open boundary
MA(I)	see NA(I)
Z1(I)	amplitudes of four tidal constituents at the first open boundary (CM)
Z2(I)	see Z1(I)
U1(I)	see Z1(I)
U2(I)	see Z1(I)
Z3(I)	amplitudes of four tidal constituents at the second open boundary (CM)
Z4(I)	see Z3(I)
U3(I)	see Z3(I)
U4(I)	see Z3(I)
V1(I)	names of special points
V2(I)	water elevation at special points (CM)
V3(I)	speed of the current at the special points (CM/SEC)

V4(I)	direction of the current at the special points
AFGN	arbitrary problem number
F	coriolis parameter (1/SEC)
G	acceleration of gravity (CM/SEC^2)
SIGMA	angular velocity of the M2 tide (RADIANS/SEC)
ALPHA	smoothing parameter
R	friction coefficient
ROL	air density (GM/CM^3)
RBETA	coefficient of geostrophic wind
C	drag coefficient
DL	$\frac{1}{2}$ step in space (CM)
DT	$\frac{1}{2}$ step in time (SEC)
T	time (SEC)
T1	interval between printouts (SEC)
T2	field output counter (SEC)
NE	field size delimeters
ME	see NE
TE	end time of computation (SEC)
KKE	number of wind fields
KO	the number of points on the open boundary minus one
IZE	number of open boundary points (first open boundary)
NG	number of points on second open boundary
IUE	twice the number of wind fields
TW	time when the wind starts
TIC	counter
LEN	see TIC

POC	see TIC
BETA	(1-ALPHA)/4
A1	2DT
A2	F(A1)
A3	R(A1)
A4	DT/DL
A5	G(A4)
C1	0 if no wind, 1 for wind
C3	C(A(2))x(10,000 is a unit conversion factor which converts (M/SEC) to (CM/SEC) after A(2) is squared
SI	time when wind stops
NURU	number of special points
NURV	printout line counter
JA	indicator, if 0 set U = V = Z = 0, if $\neq$ 0 read initial values
NEH	NE-1
MEH	ME-1
NEHH	NE-2
MEHH	ME-2
WERTO	storage location for U and V during smoothing and averaging
WERTU	see WERTO
WERTL	see WERTO
WERTR	see WERTO
WERTOL	see WERTO
WERTOR	see WERTO
WERTUL	see WERTO
WERTUR	see WERTO

WURZEL	$SQRT(ZM^2-ZST^2)$
GRZ	A3(WURZEL)

APPENDIX B

INPUT PARAMETERS AND THEIR FORMATS

The Data Input Cards

Card 1 Format 24I3

JA,NE,ME,IZE,IUE,KKE,NURU,NG

JA	indicator, JA=0, Z = U = V = 0; JA=1 read initial values
NE,ME	field size delimeters (51,51)
IZE	number of points at first open boundary (50)
IUE	double the number of wind fields (2)
KKE	number of wind field characteristics (3)
NURU	number of special points (15)
NG	number of points at the second open boundary (50)

Card 2 Format 9F8.3

AFGN,G,ALPHA,RBETA,C1

AFGN	problem number (7001)
G	acceleration of gravity (978CM/SEC^2)
ALPHA	smoothing parameter (0.998)
RBETA	coefficient of geostropic wind (0.65)
C1	wind indicator; 0=no wind, 1=wind

Card 3 Format 9F8.0

DT,TE,TW,T1,T2,SI,T,T3

DT	$\frac{1}{2}$ time step (15 SECS)
TE	length of computation (126000 SECS)
TW	time when wind starts (18000 SECS)
T1	interval between printouts (7200 SECS)

Card 3 (cont.)

T2	field output counter (0 if outputs are desired from the start of the problem; otherwise any other delayed starting time, e.g. 7200 SECS)
SI	time when the wind stops (126000 SECS)
T	time (initialized at zero)
T3	time when plots are desired (every 7200 SECS)

Card 4 Format 6E12.4

DL,F,SIGMA,R,ROL,C

DL	half the grid size (CM)
F	coriolis parameter (8.55×10^{-5})
SIGMA	angular velocity of the M2 tide (1.4088×10^{-4})
R	friction coefficient (0.003)
ROL	density of the air (1.1627×10^{-3})
C	drag coefficient (3.2×10^{-6})

Card 5 Format 24I3

NZ,MZ

NZ	N coordinate of special points
MZ	M coordinate of special points

Card 6 Format 24I3

NK,MK

NK	N coordinate of points on first open boundary
MK	M coordinate of points on first open boundary

Card 7 Format 24I3

NU,MU

NU	N coordinate of wind field delimeter

Card 7 (cont.)

MU	M coordinate of wind field delimeter

Card 8 — Format 24I3

NA,MA

NA	N coordinates of points on second open boundary
MA	M coordinates of points on second open boundary

Card 9 — Format 10A5

V(I)

V(I)	names of selected special points

Card 10 — Format 9F8.2

A(I)

A(1)	time when the wind starts (18000 SECS)
A(2)	wind speed (M/SEC)
A(3)	wind direction (in degrees in computation coordinates)

Card 11 — Format 12F6.0

HTZ

HTZ	depth cards (usually more than 10 cards; 217 in this program)

Card 12 — Format 9F8.3

Z1,Z2,U1,U2

Z1	amplitude of first component (CM)
Z2	amplitude of second component (CM)
U1	amplitude of third component (CM)
U2	amplitude of fourth component (CM)

Card 13 Format 9F8.3

Z3,Z4,U3,U4

Z3	amplitude of first component (CM)
Z4	amplitude of second component (CM)
U3	amplitude of third component (CM)
U4	amplitude of fourth component (CM)

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13. ABSTRACT

The hydrodynamical-numerical model of Walter Hansen is used to compute tidal heights and tidal currents in the Gulf of Maine. The model uses two adjacent open boundaries at which the tides are prescribed at each time step, using four tidal constituents. The grid size is six nautical miles and the time step is thirty-one seconds. Seven data runs are reported; one uses the tides and no wind and the remaining six use uniform wind fields in consort with the tides. A modified method of handling the topographic data is used. The pertinent results of the study are: (1) the use of Hansen's Model with adjacent open boundaries produces broad subjective agreement with observed data, (2) the modified method of handling topographic input data is workable, (3) wind direction and velocity produce slight variations in tidal height, (4) wind direction and velocity modify the direction of the tidal currents considerably and produce some significant increases in tidal current speed, and (5) the modifying influences of wind fields on tidal heights, tidal current velocities, and tidal current directions are more noticeable in shallow water areas than in regions of deep water.

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